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Citation for the original published paper (version of record):
Böckin, D., Willskytt, S., André, H. et al (2020). How product characteristics can guide measures for resource efficiency - A synthesis of
assessment studies. Resources, Conservation and Recycling, 154C.
http://dx.doi.org/10.1016/j.resconrec.2019.104582

Resources, Conservation & Recycling 154 (2020) 104582

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

How product characteristics can guide measures for resource efficiency — A synthesis of assessment studies

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ARTICLE INFO

Keywords:
Circular economy
Use extension
Reuse
Repair
Recycling
Life cycle assessment

ABSTRACT

A circular economy aims at decoupling value creation from resource throughput. For circular economy to contribute to environmental and resource improvements, there is need for critical assessments regarding in what general situations, beyond individual cases, solutions may lead to improvements. On the product-level, there is need for synthesized knowledge accounting for a wide range of contexts and environmental impacts. We investigate what resource efficiency (RE) measures result in reduced physical flows and environmental impacts, depending on the characteristics of products and their life cycles. The study is limited to physical measures on a product system level, irrespective of manner of implementation. A library of comparative assessments (primarily life cycle assessments and material flow analyses) was built, covering a wide range of products and RE measures. A framework was formulated for analysing for which product characteristics a measure tends to improve RE, and under which contexts there are trade-offs to take into account. For example, sharing of products is best suited for durable and infrequently used products that tend not to reach their full technical lifetime. A trade-off is that sharing can increase transportation for accessing shared stock. The identified key product characteristics were: whether products are consumable or durable, active or passive, typically used for their full technical lifetimes or discarded before being worn out, the product's frequency of use and whether function remains at a product's end of use. Pace of development matters for suitability of measures for active, durable products, while complexity is relevant for restorative measures and recycling.

1. Introduction and aim

Circular economy (CE) is the most recent response to growing concerns over resource use and associated waste. This concern is not new, and was strongly articulated in the seminal work by Meadows et al. (1972). Over the years the discussion on waste and material resources, and the need to decouple resource use and economic growth, has re-emerged in waves (Blomsma and Brennan, 2017).

Central to circular economy is the discussion on different measures to achieve resource efficiency, measures such as recover, recycle, remanufacture, reuse or reduce resource use in production. The different measures have been structured in so called R-frameworks, e.g. 3Rs, 4Rs, 6Rs and 9Rs, the majority of which set priorities between measures (Kirchherr et al., 2017).

The most prominent example is perhaps the European Commission's (EC) waste hierarchy which prescribes the following order of priority in waste legislation and policy: prevention, preparing for reuse, recycling, recovery and disposal. Still, exceptions are recognized and priorities for specific waste streams may depart from the hierarchy when justified by life-cycle thinking (EC, 2008a). Kirchherr et al. (2017), who review 114 different definitions of CE, strongly emphasise the need for priorities between measures, in order for CE to provide ample guidance and not allow for greenwashing. However, the strategies outlined in the R-frameworks are idealised descriptions without accounting for real-world conditions like combinations of measures, insufficiently exploited lifetimes, low collection rates and losses in remanufacturing, repair and recycling (Ljunggren Söderman and André, 2019). The real benefits of measures may thus be significantly smaller than the idealised ones and rankings may even shift if conditions are unfavourable (Ljunggren Söderman and André, 2019). Although the general environmental appropriateness of the waste hierarchy may be possible to demonstrate on the level of some materials, e.g. Tillman et al. (1991), its applicability to any material and to products with components of many different materials may be questioned. Further, measures can be interdependent, as recognised by Blomsma and Brennan (2017), who introduce the concept of *circular configurations* for several different measures working

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https://doi.org/10.1016/j.resconrec.2019.104582
Received 30 March 2019; Received in revised form 31 October 2019; Accepted 2 November 2019
0921-3449/

together in sequence or parallel. They also call for assessments, using e.g. life cycle assessment (LCA) or material flow analysis (MFA), to systematically investigate circular configurations in different and real-world contexts. This can enable learning about the configurations and their interdependencies, but also aids in assessing in what contexts measures are effective.

There is a growing number of comparative assessment studies of measures for CE. Some synthesising efforts that take a sector or industry perspective exist. For instance, Ghisellini et al. (2018) reviewed comparative assessments of the environmental and economic consequences of CE measures in the construction industry. Kjaer et al. (2018) developed a framework for environmental assessment of product-service-systems and used it on examples from the textile industry. Furthermore, there is a stream of research on simulation-based optimisation and assessment of products, mainly applied to metal-containing products and recycling systems (as reviewed by Reuter (2011)). Additional studies organised around industries include one by the Royal Swedish Academy of Engineering Sciences (IVA, 2015). However, what industry a product belongs to is not necessarily the most important factor determining what measures for CE are effective. Other characteristics of the product (or its context), such as complexity or lifetime, may be more important. Further, if it can be determined what product characteristics govern the effectiveness of CE measures, this would allow for learning from assessment studies between product categories and between industries. For these reasons, we reviewed comparative life-cycle based assessment studies of CE measures applied to a wide variety of products, seeking synthesized conclusions. Reviewed studies were on a micro level, i.e. product or product chain level.

We draw on the works of Blomsma and Brennan (2017) and recognise the interdependence between measures and their context-dependent outcomes, as also confirmed in recent work on use extension and recycling of electronics (André et al., 2019; Ljunggren Söderman and André, 2019). Additionally, we recognize that not all measures are suitable, or even applicable, to all types of products. Rather, we seek knowledge on what measures are appropriate, or possible, to implement, and their effectiveness in terms of resource efficiency (RE), depending on the characteristics of a product and the context of its life cycle. Several studies point to the potential trade-offs associated with such RE measures, e.g. between types of resource use and environmental impact and between different stages in the life cycle (Haupt and Zschokke, 2017; Kjaer et al., 2018; Ljunggren Söderman and André, 2019). However, to the authors' knowledge there have been no attempts to organise or systematically analyse such trade-offs.

The aims are thus to synthesise existing assessment studies to investigate the following questions:

- What RE measures are suitable to apply, in terms of their outcome for resource use and environmental impact, depending on the characteristics of products and their life cycles?
- Which are the trade-offs associated with RE measures, e.g. between different types of resource use and environmental impact and between different stages in the life cycle?
- What key product characteristics can be identified as decisive for the outcome of RE measures?

The term resource efficiency (RE) rather than circular economy is used, in order not to delimit to measures explicitly aiming for circular flows (e.g. reuse, repair, recycle) but include also measures taken in production stages. We define RE as fulfilling the same function causing less resource use and environmental impact. The term *product* is used to denote both products, services and combinations thereof, conforming to the standard for LCA of the International Organization for Standardization (ISO, 2006). Only measures of *physical* nature aimed at RE were included, in contrast to organisational and administrative measures such as new business models and policies. Organisational and administrative measures must eventually affect physical flows to make a difference, why knowledge on physical measures is a necessary precondition for other measures to be environmentally beneficial.

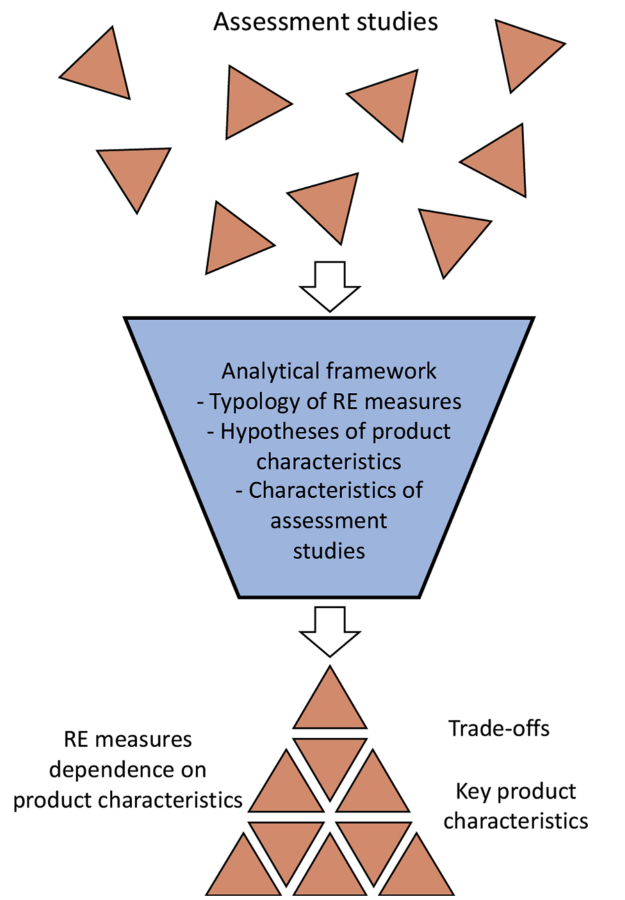

Fig. 1. Conceptual representation of the method, including the creation of a library of studies, extraction of relevant information by using an analytical framework and synthesis of the extracted data.

Regarding assessments of RE measures, the synthesis is mainly delimited to studies of LCA and MFA types, which are applicable to all kinds of products and RE measures. There are also thermodynamically based simulation methods, which model recycling systems with a higher level of detail (Reuter, 2011; Reuter et al., 2015). Such studies were however left outside the scope since they have primarily been used for creating detailed life cycle inventories in cases of recycling of metal-containing products. Furthermore, *economic and social aspects* of RE measures are outside the scope of the paper. An effort was made to include cost aspects, but too few life-cycle based assessment studies combining economic and environmental aspects were found to allow for generalisation. Also rebound effects were excluded, although warnings exist that resource efficiency gains are likely to be reduced by rebound effects (Zink and Geyer, 2017). Again, this is because rebound is handled to a very limited extent in the reviewed assessment studies.

2. Methodology

An illustration of the overall methodology can be found in Fig. 1. Initially, assessments of a wide selection of RE measures applied to a wide variety of products were collected into a library. Studies were then analysed using an analytical framework developed for the purpose of extracting information of relevance for RE. The analytical framework consists of a typology of RE measures and of a list of product characteristics of relevance for RE. This was complemented by characterisation of each study as such (including e.g. its methodology and results). The framework was used to extract and organise relevant information in a database. Extracted data was filtered and processed to allow for synthesis and identification of patterns regarding how RE measures depend on product characteristics, as well as identification of trade-offs and key product characteristics. The entire process was iterative, as analysis of assessment studies prompted further developments of the framework, and led us to reclassify studies and to expand the library with additional assessment studies.

Synthesis of knowledge across types of products, RE measures and industrial sectors was prioritised over completeness in data collection. Hence, the library was not an exhaustive collection of assessment studies investigating RE measures for different products.

2.1. Literature search and selection

The search for comparative environmental assessment studies focused on studies using LCA, simplified LCA or MFA for investigating products or services after potentially introducing RE measures, compared to a more conventional product system. Two main sources were used: (1) literature, both from peer-reviewed journals and grey literature and (2) studies conducted by companies and/or academic partners within the Mistra REES research programme, within which the present research has been carried out (Mistra REES, 2019).

Literature was searched by using combinations and variations of the following search terms in Scopus, Web of Science and Google Scholar: Life cycle assessment, material flow analysis, circular economy, resource efficiency, material use, product, service, PSS, manufacturing, maintenance, repair, reuse, remanufacturing, repurposing, prolonged life, use extension, sharing, functional sales, durable, modular and eco-design. The search was conducted during the autumn of 2016 to the spring of 2017.

To include studies of measures taken in production, the collection was complemented with assessment studies of cleaner production efforts. These were not retrieved through a systematic search process, the body of literature being far too comprehensive. Instead a few example studies were added to the library chosen on an ad-hoc basis. Furthermore, in order to focus the study, assessments comparing waste management options were not included except for a few studies on recycling options for electronics and paper, also these chosen ad-hoc.

The following criteria were used for adding studies to the library. Firstly, that a wide range of RE measures and types of products and industries should be covered. Secondly, each assessment should allow for comparisons between one or several RE measures and a baseline alternative. Thirdly, studies should be well-documented and transparent regarding results and methodological choices.

In total, 59 assessment studies were collected for further analysis, 50 of which were found in literature and 9 were collected from Mistra REES. The studies encompassed 124 cases in total, covering a wide range of product types and industries.

2.2. Analytical framework

The analytical framework consists of three parts: 1) a typology of RE measures which can be applied to a product system, 2) a list of characteristics of product systems hypothesised to be of importance for the outcome of RE measures and 3) a way to describe assessment studies of RE measures in a comparable and concise manner. A first version of the framework was presented by Willskytt et al. (2016) and applied by Böckin et al. (2016).

2.2.1. Typology of physical measures for RE

A list of physical measures for increased RE was established. It was divided into three main categories, distinguished by where in the life cycle the measure can be undertaken: *extraction and production*, *use phase* and *post-use*.

These main categories were further detailed to form a typology of physical RE measures (see Fig. 2). While the presented typology is of our own design, and is organised according to a product life cycle, it draws on existing frameworks in the CE literature (Allwood et al., 2011; EC, 2008a; EMF, 2013; Potting et al., 2017; Stahel, 2010; Stahel and Clift, 2016) and is complemented by definitions found in literature (of remanufacturing (Sundin, 2004) and functional recycling (Graedel et al., 2011; Guinée et al., 1999)). The typology also draws on eco-design literature such as the Ten golden principles (Luttropp and Brohammer, 2014), the Eco-design strategy wheel (Brezet and van Hemel, 1997) and other eco-design guidelines as described by e.g. Ceschin and Gaziulusoy (2016) and Sundin (2009).

A common way of achieving RE is reducing material and energy use in the **extraction of raw materials and production of materials and products**. This can be accomplished through *reducing losses* of material or energy in production, e.g. by reintroducing scrap and energy flows into the production process or by valorising them in other production chains, through industrial symbiosis or process integration. The *quantity of material can be reduced*, while still using the same material in the product. The *material composition of products can be changed*. For example, fossil, hazardous or scarce materials can be substituted and recycled material can be used instead of primary material. Material substitution can increase RE in itself (e.g. through excluding hazardous constituents) or enable other measures (e.g. increase technical lifetime through increased durability). Reducing or changing materials requires that the product is redesigned.

The use of a product can be improved in two principal ways, through **using the product effectively and efficiently** and through **extending its use**.

Use effectively means to deliver (which is relevant for a provider) or acquire (which is relevant for a customer) function according to the user's needs but not more, where an example is smart dispensing of soap. Effective use also includes making sure the product is used for its intended purpose, and to increase the functionality of products in order to improve system efficiency, such as detergents allowing for lower washing temperatures. Using a dissipative product effectively is analogous to efficient use of the corresponding active product (e.g. when it comes to water use in a building). *Reduced use of auxiliary materials and energy*, such as energy efficiency improvements, also belong to the group of use-phase efficiency, as does *sharing* a product between several users.

To **extend the use** of products means to prolong their lifetime. This can be done by *using more of the technical lifespan* of the product, by the same user or a new one (the latter often denoted reuse). The product may also be redesigned for *increased technical lifetime*, and a disposable product can be re-designed to a *multiple-use product*.

The use of a product may also be extended through restorative interventions such as *maintenance*, *repair*, *remanufacturing* or *repurposing*. *Maintenance* involves activities where products are inspected, maintained and protected before breakdown or other problems occur. *Repair* takes place after wear, malfunction or failure. *Remanufacturing* is the process of restoring a product to a state as good as new or even better, through disassembly, repair or exchange of components, re-assembly and quality assurance. *Repurposing* means reuse of a product in a different function than the original one.

The last category, **post-use**, addresses the end-of-life of products and components. *Recycling* recovers and returns materials to use. In recycling without quality loss, the properties and function of a material are maintained, why the recycled material can replace virgin raw materials and be used for the same function. However, recycling usually leads to quality loss, in which the material properties (and hence also function) deteriorate.

Biodegradable materials can be *digested anaerobically* or *composted* (yielding e.g. biogas, recovered plant nutrients and landscaping material). *Energy recovery* converts the energy stored in materials into usable energy carriers such as heat and electricity. *Landfills* are constructed for limiting the environmental impact of disposing discarded products and may include landfill gas collection for energy recovery.

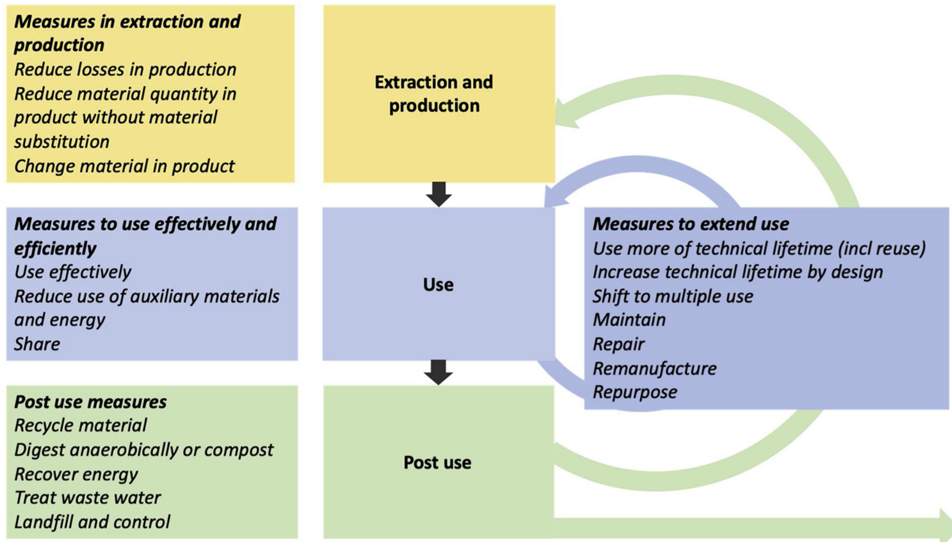

Fig. 2. Typology of physical RE measures.

Note that design changes are a necessary precondition for many, if not most, of the measures. Consequently, design is not included as an explicit measure in the typology but is instead an inherent aspect of most measures.

2.2.2. Characterisation of product systems

The second part of the framework was a list of characteristics of product systems (see Table 1). Each entry represents a characteristic that we hypothesise is relevant for the outcome of RE measures. For example, we expect that whether products are possible to disassemble has implications for remanufacturing and repair.

All potentially relevant characteristics identified were grouped into six categories (see Table 1). The right-most column instructs how the data corresponding to each characteristic were mapped when analysing assessment studies. The first category represents various use aspects. We distinguish between consumable and durable products, since they allow for different RE measures. Consumable products were divided into disposable ones (e.g. packaging, tissue) and those used in a dissipative manner (i.e. practically “consumed” during use such as food and fuels). Selected aspects pertinent to durable products were identified from literature on R-frameworks for circular economy, as reviewed by Kirchherr et al. (2017), i.e. lifetime, frequency and intensity of use and need for energy, auxiliary materials or maintenance during use. The second and third categories include the complexity of products in terms of number of components and materials as well as the possibility to disassemble for remanufacturing, upgrading, repairing or recycling. They were chosen based on literature on eco-design and design for X, e.g. Sundin (2009) and Ceschin and Gaziulusoy (2016). The next category is *content of concern*. Content of hazardous (e.g. toxic) materials is often mentioned in eco-design guidelines, e.g. Luttropp and

Table 1
List of product system characteristics believed to be relevant for RE.

Type of characteristic	Product characteristic	Entry used for database
Use aspects	Consumable	Yes/No
	- Disposable	Yes/No
	- Consumed dissipatively	Yes/No
	Durable	Yes/No
	- Technical lifetime	Measured as time, number of uses or delivered function such as distance or number of rotations
	- Intensity of use	Time per use: Low < 30 min; Medium 30 min–2 h; High > 2 h
	- Frequency of use	Number of uses per period: Low = few times/year; Medium = once/month; High = at least once/day
	- Requires auxiliary material or energy during use phase	Active or passive*
	- Maintenance needs of product/service	Free text
	- Need for auxiliary components during maintenance	Free text
	Environmental relevance of user behaviour	Describe in what way user behaviour affects total impacts
Complexity	Number of components in product	Low 1–20; Medium 20–50; High > 50
	Number of materials in product	Low 1–20; Medium 20–50; High > 50
Possibility to disassemble	…for remanufacturing/repair/upgrading	Yes/No. If Yes, exemplify how disassembly was enabled (free text)
	…for recycling	Yes/No. If Yes, exemplify how disassembly was enabled (free text)
Content of concern	Scarce materials	Yes/No, according to list of geochemical scarcity (Skinner, 1976)
	Hazardous substances	Yes/No, according to lists of restricted hazardous substances and materials (EC, 2008b; Eurostat, 2016)
System characteristics	Dominant life cycle phase	Indicate the life cycle phase that dominates environmental impacts and resource use
	Industry	According to the Swedish Standard Industrial Classification, *SNI 2007* (Statistics Sweden, 2007)
	Development pace in terms of efficiency, functionality, appearance	Indicate type and pace of development from low to high

* Active products use energy and/or auxiliary materials in the use phase, whereas passive do not.

Brohammer (2014). Content of scarce material was included since scarce materials are often overlooked in LCA studies, although natural resources is defined as an area of protection in LCA (ISO, 2006). Content of critical materials was not included since criticality indicates supply risks for economically important materials (Graedel and Reck, 2016) rather than RE as here defined. Finally, on the system level, we noted which life cycle phases dominate environmental impact and resource use. Also, we included the type of industry, since it has been used as a basis for CE research, by e.g. Ghisellini et al. (2018), Kjaer et al. (2018) and IVA (2015). Development pace in terms of efficiency, functionality and appearance was included based on studies of product obsolescence, e.g. Cooper (2010) and Proske et al. (2016b).

2.2.3. Characterisation of assessment studies

The last part of the framework was used to characterise the studies by noting aspects such as type of product (or system or component), the goal of the study and methodological choices like assessment method, system boundaries, functional unit, indicators used and key assumptions.

Subsequently, the key results of assessment studies were summarised. The results were first noted for each assessed scenario in each study, in terms of the various indicators used. To enable an overview they were classified into indicators for *material efficiency*, *energy efficiency* and *environmental performance*, each expressed as a percentage improvement or deterioration. Material efficiency represents a reduction of an indicator for use of natural resources (other than energy), either in direct quantities such as kg material or m^2 land, or expressed as LCA impact category indicators for resource use. Energy efficiency represents a reduction in the quantity of energy used. Finally, environmental performance represents the impacts of various emissions on the natural environment and human health, in terms of e.g. global warming potential and ecotoxicity potential.

The numerical results regarding improvement/deterioration were taken as-is from each study, since the varying methodological choices and scopes between studies made it unfeasible to compare their precise numerical results. Instead the numbers were simplified. An improvement by more than 2.5% was denoted a plus sign (+) and a deterioration by more than 2.5% a minus sign (−). Undecisive results, between +2.5% and −2.5%, were denoted zero (0). Additionally, (0) was used in cases where different environmental impact categories showed conflicting results. The number of 2.5% is seen as suitable for the purposes of the analysis. Additionally, key aspects to which the results were reported to be most sensitive, dominant life cycle phase, and trade-offs between life cycle phases or environmental impacts were noted and general conclusions of the study were summarised.

Finally, for every case it was noted whether there were associated changes in design, policy or business model that played a role in the assessment, although no analysis of policy and business model aspects was carried out in this paper.

2.3. Analysis procedure

The full analytical framework described above was used by the authors to analyse the collected assessment studies and synthesise learnings from them.

Frequently, more than one physical measure was assessed in the same study. If interdependent, they were noted as primary, secondary and tertiary measures. In some studies, several measures were investigated in parallel without interdependencies. Although not ideal, the same terminology was then used. i.e. primary, secondary and tertiary measures.

The extracted information was listed in a database (see supplementary file in Appendix A), which allowed sorting and analysis across cases, on many levels and dimensions. To address the research questions, a systematic mapping was made, of measures, product characteristics and corresponding results in terms of material efficiency, energy efficiency and environmental performance. The cases were subsequently filtered and sorted by positive or negative results. This sorting allowed us to test the relevance of each product characteristic in Table 1 by identifying characteristics that correlated to improvements in material and energy efficiency and environmental performance. Several results could be generalised and, based on the findings, a number of key product characteristics were identified that are decisive for the outcome of RE measures.

3. Analysis

The following section presents what types of RE measures are suited for what types of products. The structure follows the typology of RE measures (see Fig. 2), with the exception of anaerobic digestion, composting, energy recovery and landfilling for which no cases were collected. For each measure, first the specific cases in the library are presented in order to identify what product characteristics correlate with improved results (tables summarising the cases and their results are provided in each subsection, while the full details are available in the supplementary material). Findings are then generalised if possible, and potential trade-offs are identified. Note also that some cases have been aggregated so that the total number of cases appears to be lower than 124.

3.1. Extraction and production

3.1.1. Reduce losses in production

The studies of *reduction of losses in production* show that this measure often improves material efficiency (see Table 2). Unnecessary raw material production can be avoided, and the larger the impacts from production, the larger the benefits of this measure. However, the improved material efficiency does not always lead to improved energy efficiency or environmental performance (Berlin and Sonesson, 2008; Malinauskienė et al., 2016). Malinauskienė et al. (2016) show that reducing production losses can come at the cost of increased energy use.

3.1.2. Reduce material quantity in product without material substitution

None of the cases investigate reduced material quantity without material substitution as their main RE measure. However, in general a reduction of material quantity without material substitution grants environmental benefits as long as the function of the product does not deteriorate, like if the durability is decreased as a result of use of less

Table 2
Studies assessing the reduction of losses in production, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Food (dairy)	Optimisation of production sequences for waste reduction in dairy production	+	n.a.	0	Berlin and Sonesson (2008)
Paper	Reduced energy use in production by localisation to reduce transportation needs	n.a	0	0	Counsell and Allwood (2007)
Metals	Reduced losses by …automated laser cutting	+	+	n.a.	Malinauskienė et al. (2016)
	…jet stream cutting	+	–	n.a.	
Incontinence product	Recycling and reuse of production waste vs. incineration with energy recovery	+	n.a.	+	Willskytt and Tillman (2019)

Table 3
Studies assessing the change of material in products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Transparent electrode	Graphene vs. indium	–	+	n.a.	Arvidsson et al. (2016)
LED lighting product	Eco-design: e.g. recycled PET and Al in heat sinks, modular luminaire	+	n.a.	+	Casamayor and Su (2013)
Paper	Paper based on crops vs. wood	n.a.	+	+	Counsell and Allwood (2007)
Cotton	Organically grown vs. conventional cotton	n.a.	n.a.	+	Esteve-Turrillas and de la Guardia (2017)
	Recycled vs. conventional cotton	n.a.	n.a.	+	
Cup	Paper-based vs. poly-styrene-based material	+	n.a.	+	Ligthart and Ansems (2007)
Car	Bio-based by-product as filler in PP-composite vs. talc	+	+	+	Luz et al. (2010)
Metals	Increased use of secondary metals, instead of primary	+	0	n.a.	Malinauskienė et al. (2016)
Lithium-ion battery for electric vehicle	Iron-phosphate in cathode, vs. material containing cobalt	0	–	+	Reuter (2016)
Textile	Eucalyptus-based tinsel, vs. conventionally produced cotton	+	n.a.	0	Roos et al. (2015)
Incontinence product	Increased content of bio-based material, vs. fossil-based	0	n.a.	+	Willskytt and Tillman (2019)

material.

3.1.3. Change material in product

Changing material in a product can be a stand-alone measure, like substituting scarce metals (Arvidsson et al., 2016; Reuter, 2016) or switching to recycled materials (Casamayor and Su, 2013; Esteve-Turrillas and de la Guardia, 2017; Malinauskienė et al., 2016) or renewable materials (Willskytt and Tillman, 2019), (see Table 3). A change of material can also be a precondition for other measures, for example lightweighting or remanufacturing (see Tables 5 and 10). The variety of products in Table 3 prevents general conclusions to be drawn, with the exception that material substitution often implies a risk for burden-shifting between different types of impact. Examples include substitution of indium with graphene leading to improved energy efficiency, but also an increased use of copper (Arvidsson et al., 2016), the reduction of global warming potential by increasing bio-based content at the cost of increased land use (Willskytt and Tillman, 2019) and the substitution of cobalt in batteries leading to lower battery efficiency (Reuter, 2016). There can also be positive secondary effects, such as when substituting hazardous materials yields benefits in later life cycle stages, e.g. recycling.

3.2. Use efficiently and effectively

3.2.1. Use effectively

A product can be used more effectively by minimising losses in use or by avoiding mismatches between the product and the user's needs. Examples include a waste-collection service (Bonvoisin et al., 2014), a water-purification service (Chun and Lee, 2016), façade cleaning (Lindahl et al., 2014) and incontinence products (Willskytt and Tillman, 2019) (Table 4). In the study by Bonvoisin et al. (2014) sensors enabled optimisation of waste collection. Several eco-design measures were investigated separately which in isolation did not improve RE, though a combination of them did. For the water-purification service, the provider offers education to the user and regular maintenance and repairs. In the case of façade cleaning, the use of ultra-clean water eliminated the need for chemicals, improving system efficiency. For incontinence products, the producer offers measurements of degree of incontinence and body size and then recommends appropriate levels of protection for each user.

In general, user behaviour affects the results of the measure *effective use*. Business models (e.g. service provision) and education can play important roles in enabling changed user behaviour, while product design can potentially remove the dependence on user behaviour altogether. An example is an electronic product designed to be turned off when unused, instead of staying in a power-consuming mode, such as LED lighting with motion sensors (Ljunggren Söderman and André, 2019). However, using sensors to enable effective use can come at the cost of increased abiotic resource depletion (Bonvoisin et al., 2014).

3.2.2. Reduce use of auxiliary materials and energy

Less material or energy use during the use phase often leads to increased RE. The cases in Table 5 include buildings, vehicles and service provisions, in which efforts to decrease use-phase impacts were studied, e.g. by lightweighting vehicle components (Böckin and Tillman, 2019; Kim and Wallington, 2013; Soo et al., 2016), by adding a layer of insulating façade to a building (Ingrao et al., 2016) or by reducing the need for chemicals in cleaning operations (Larsson, 2009). All are *active products*, which means that they require electricity, fuels or chemicals during their use phase. However, there are trade-offs involved with increased use-phase efficiency. It often requires more efforts in production, which may not pay off in terms of reduced life cycle impacts (Henßler et al., 2016; Pomponi et al., 2016). For vehicles, lightweighting can significantly decrease fuel consumption (Böckin and Tillman, 2019; Kim and Wallington, 2013; Luz et al., 2010), but at the cost of using highly impacting materials (Böckin and Tillman, 2019; Soo et al., 2016) or less durable components (Schau et al., 2012). For buildings, improved insulation decreases energy use, but requires more material (Ingrao et al., 2016; Pomponi et al., 2016).

3.2.3. Share

Sharing products among users was found to improve RE for durable products that are not used frequently or intensely, and not easily worn or damaged. Examples range from leasing of gardening equipment to sharing of bicycles and washing machines (Table 6). Sharing schemes can reduce impacts (Amaya et al., 2014; Hu et al., 2012; Mont, 2004),

Table 4
Studies assessing the effective use of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Waste collection	Using ICT to optimise waste collection system and reduce transportation	–	n.a.	+	Bonvoisin et al. (2014)
	…plus various (isolated) eco-design measures	–	n.a.	+	
	…combined eco-design measures	0	n.a.	+	
Water purification system	Renting a water purifier vs. owning it (service from PSS provider)	–	n.a.	+	Chun and Lee (2016)
Façade cleaning	Cleaning with ultra-clean water, vs. using detergent and high-pressure water	n.a.	n.a.	+	Lindahl et al. (2014)
Incontinence product	Customization of products by using measurements instead of staff´s knowledge	+	n.a.	+	Willskytt and Tillman (2019)

Table 5
Studies assessing reduced use of auxiliary materials and energy for products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Truck engine (additive manufacturing)	Additive manufacturing of engine parts to reduce vehicle weight	n.a.	n.a.	+	Böckin and Tillman (2019)
Vehicle with hybrid propulsion	Hybrid propulsion vs. propulsion by internal combustion engine	–	+	+	Henßler et al. (2016)
Wall	Improved insulation with an air-gap and expanded poly-styrene panels	n.a.	n.a.	0	Ingrao et al. (2016)
	Ventilated vs. standard façade with rock-wool or PET panels for insulation	n.a.	n.a.	+	
Vehicle with material substitution	Lighter weight by changing material to different metals and plastics	n.a.	+	n.a.	Kim and Wallington (2013)
	Lighter weight by partially changing to magnesium	n.a.	0	n.a.	
Floor care service	Cleaning with special polishing pad and water, vs. conventional pad and detergents	+	n.a.	+	Larsson (2009)
Building façade	Adding extra façade to reduce energy losses	–	+	+	Pomponi et al. (2016)
T-shirt	Lowered washing temperature and more sustainable transportation to buy t-shirt	n.a.	n.a.	+	Roos et al. (2015)
Vehicle door	Light-weight door, vs. conventional	–	n.a.	+	Soo et al. (2016)

although there is also a risk of increased impacts from associated transportation. Examples of increased transportation impacts include the cases of shared clothes, drills and lawnmowers (Mont, 2004; Roos et al., 2015), as opposed to cases where car transportation was not required (Amaya et al., 2014; Hu et al., 2012).

More generally, sharing can increase RE for products that are usually discarded before reaching their full technical lifetime, e.g. computers or clothes. Sharing increases the frequency of use, allowing more function to be provisioned before such products become obsolete. Conversely, for products that tend to be used for their full technical lifetimes, sharing gives no net change in material flow per delivered function. Sharing wears out such products more quickly, after which they need to be replaced. From this follows that car sharing schemes only reduce environmental impact if the total kilometres driven per vehicle increases and rebound effects are avoided, i.e. no increase in kilometres driven per person.

3.3. Extend use

RE can also be improved by extending the use phase, e.g. through increased lifetime, multiple use or restorative actions. Use extension is relevant only for durable products and for redesign of disposable products for multiple use. For *active products,* an important trade-off occurs when technological developments lead to rapid efficiency improvements in the use phase, in which case it can be more efficient to replace an active product than to extend its use (although the trade-off can be avoided if it is possible to upgrade the efficiency of products). This trade-off has previously been described by e.g. ISO (2002), and will henceforth be referred to as "use-phase efficiency vs. use extension". Numerous examples can be found concerning cars (Smith and Keoleian, 2004; Spielmann and Althaus, 2007), washing machines (Ardente and Mathieux, 2014a), and other household appliances (Bobba et al., 2016; Boustani et al., 2010; Domenech and Van Ewijk, 2015; Iraldo et al., 2017). Another trade-off is that there is a risk of use-extension measures keeping products containing hazardous substances in use.

3.3.1. Use more of technical lifetime (including reuse)

The RE of products that tend to be discarded before the end of their technical lifetime can be improved by prolonging their use, by the same user or a new one. Studies include electronic products, vehicles and clothes (Table 7). This measure may increase RE for passive products like furniture (Castellani et al., 2015), although benefits can be counteracted by transportation (Roos et al., 2015). For active products, the measure improves RE in most studied cases, although the trade-off with "use-phase efficiency vs. use extension" comes into play. User behaviour affects whether more of the technical lifetime can be used, for example when users decide to prematurely discard products. This could be improved by e.g. education campaigns, smart design and by providing infrastructure for product reuse (Ljunggren Söderman et al., 2011).

3.3.2. Increase technical lifetime by design

In contrast to using more of the lifetime of an existing product, the product can be re-designed to last longer. This measure is more relevant for products that tend to be used until they break down. Examples in Table 8 include electronics, vehicles and household appliances. For LED lighting, an increased number of chips enabled lower thermal stress and thus improved durability (Ljunggren Söderman and André, 2019). For household appliances, improved durability can come at the cost of using more, or more impacting, materials, e.g. by increasing the amount of copper in a refrigerator's cooling system (Iraldo et al., 2017; Ljunggren Söderman and André, 2019). There are also potential drawbacks associated with this measure. For household appliances and LED-lighting, the trade-off "use-phase efficiency vs. use extension" comes into play (Ardente and Mathieux, 2014a; Iraldo et al., 2017).

3.3.3. Shift to multiple use

Disposable products can often be redesigned for multiple use. Examples include incontinence products, temporary buildings and a machine component (fuel filter) (Table 9). All cases required a radical redesign of the product itself and/or of the associated maintenance system. The possibility to clean the product between uses is usually a requirement. In theory, any consumable product can be redesigned for multiple use, except for dissipatively used products like food, detergents and fuels. For this measure there are typically trade-offs, as evidenced by the varied results presented. More energy and materials is usually invested in producing a multiple-use product, which can only pay off by using the product enough times. Furthermore, impacts associated with maintenance and cleaning may outweigh benefits from avoided production in the single-use alternative. For instance, the bed

Table 6
Studies assessing sharing of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Bicycle	Sharing of bikes, with varying levels of robustness, maintenance and redistribution, vs. self-owned	n.a.	n.a.	+	Amaya et al. (2014)
Library books	A 20 % increase of library stocks reduces private consumption	0	n.a.	n.a.	Domenech and Van Ewijk (2015)
Washing machines	Sharing between households, vs. one machine per household	+	n.a.	+	Hu et al. (2012)
Drills and lawnmowers	Sharing drill or lawnmower between neighbours, instead of owning	n.a.	n.a.	+	Mont (2004)
	Renting drill or lawnmower, instead of owning, implying increased transportation to access	n.a.	n.a.	–	

Table 7
Studies assessing more use of the technical lifetime of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Laptops	Reuse of laptops to extend the use phase (from 3 to 6 years)	+	n.a.	+	André et al. (2019)
2nd hand store (E.g. clothes, furniture, books, glasses)	Purchase of a second-hand item instead of new	+	n.a.	+	Castellani et al. (2015)
Bearings (in gearboxes, engines, and wheels)	Bearings in a PSS solution (reuse, remanufacture and robust design) vs. conventional product sales	+	n.a.	n.a.	Diener et al. (2015)
Ship hull	Reuse of a ship hull that forms the basis of a new ship vs. no reuse	n.a.	n.a.	+	Gilbert et al. (2017)
Notebook computer	Reuse of laptops to extend the use phase (from 3 to 6 years)	+	n.a.	n.a.	Ljunggren Söderman and André (2019)
"Eco-cycling park"	2nd hand-store co-located with recycling station vs. regular recycling	n.a.	+	+	Ljunggren Söderman et al. (2011)
Bicycle	Purchase of a pre-owned vs. new bicycle	n.a.	n.a.	+	Ong (2016)
T-shirt	Service life increased X4 through clothing library …plus short transport (car)	n.a.	n.a.	+	Roos et al. (2015)
	…plus long transport (car)	n.a.	n.a.	0	
	…plus long transport (bus)	n.a.	n.a.	+	
	…plus long transport (bus/car)	n.a.	n.a.	–	
T-shirt	Favourite t-shirt's service life increased X5	n.a.	n.a.	+	Roos et al. (2015)
Car	Moderately or considerably extended lifetime	n.a.	n.a.	0	Spielmann and Althaus (2007)
Electrical and electronic equipment	Selling reused vs. new products	+	n.a.	n.a.	Tasaki et al. (2006)
	Leasing vs. selling new product	+	n.a.	n.a.	

pans in the study by Sørensen and Wenzel (2014) need to be washed at high temperatures (with fossil-based electricity), giving a lower RE than the single-use alternative. Other studies of multiple-use health-care products show considerably smaller impacts from washing (Willskytt and Tillman, 2019).

3.3.4. Maintain, repair and remanufacture

The use of durable products can be extended by restorative interventions like *maintaining*, *repairing* and *remanufacturing*. Maintenance usually requires little intervention, while repair and especially remanufacturing might require significant intervention including replacement of parts. Remanufacturing can also involve upgrading of the product to current levels of fashion, function or efficiency. The studied examples include electronics, buildings, vehicles and household equipment (Table 10).

Maintenance has a large potential for reducing environmental impacts by prolonging the life of products (Carlisle and Friedlander, 2016; Chen and Lu, 2017). One trade-off identified was between benefits from increased maintenance and impacts from increased transportation of materials or personnel. Maintenance in a PSS is often done by visiting service personnel, as exemplified by a rental model for a water purification (Chun and Lee, 2016).

Repair and *remanufacturing* mostly improve RE, e.g. when remanufacturing compressors (Biswas et al., 2013) and car engines (Smith and Keoleian, 2004). However, several entries show negative results, e.g. due to the trade-off "use-phase efficiency vs. use extension". In the case of remanufacturing of alternators (Schau et al., 2012), redesign for lightweighting was also considered, but the lower weight caused the product to be less durable. Finally, Kerr and Ryan (2001) and Proske et al. (2016a) show that modular designs allowing for repair and remanufacturing can often improve RE, although Proske et al. (2016a) also show that material use can increase, in this case due to an increased need for connectors.

3.3.5. Repurpose

Repurposing potentially increases RE when the remaining functionality is insufficient for the original purpose (Table 11). One study argues that due to fast technological development a refurbished smartphone replaces a new smartphone to a very limited extent and concludes that repurposing into a parking meter is more beneficial (Zink and Maker, 2014). Another example of repurposing is lithium-ion batteries in electric vehicles, which after some years cannot fulfil vehicle requirements. The used battery can in a "second life" instead be repurposed for stationary energy storage in e.g. home solar PV systems (Olofsson and Romare, 2013).

3.4. Post-use

3.4.1. Recycle material

Use of recycled material can decrease the input of primary raw materials to a product system. RE can be improved by recycling as long as impacts from recycling are smaller than impacts from primary material production. Table 12 shows examples including recycling of electronics and paper, all of which improve RE. Most types of products, except those used in a dissipative manner, can be recycled if collected and if suitable recycling technology is in place. The measures for product use extension interplay with recycling, since not all collected products will be reusable and parts need to be replaced during maintenance, repair and remanufacturing. In contrast to several other RE measures, recycling extends the use of materials rather than products or components. Recycling requires separation of products' constituent materials why the recyclability highly depends on the complexity and level of integration of the product.

The environmental potential for recycling lies with products whose material production dominates life cycle impacts. A good example is aluminium packaging, since the production of aluminium from bauxite is much more energy intensive than the recycling processes e.g. Tillman

Table 8
Studies assessing increased technical lifetime of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Household appliances	Extended lifetime by increased durability …for a refrigerator	+	0	0	Iraldo et al. (2017)
	…for an electrical oven	+	0	0	
Car	Extended lifetime by one year	+	n.a.	+	Kagawa et al. (2006)
LED lighting product	Modular design and more LED chips extend component use life	+	n.a.	n.a.	Ljunggren Söderman and André (2019)

Table 9
Studies assessing a shift to multiple use of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Fuel filter	Reusable vs. disposable fuel filter	+	+	+	Bergstrand and Jönsson (2017)
Paper	Un-printing office paper for multiple use vs. single use	n.a.	+	+	Counsell and Allwood (2007)
Office paper	Un-printing office paper for multiple use vs. single use	+	n.a.		Domenech and Van Ewijk (2015)
Bed pads	Reusable and washable bed pads vs. disposable	n.a.	n.a.	–	Helgestrand et al. (2011)
Cup	Reusable vs. disposable cup …made of earthenware	–	n.a.	–	Ligthart and Ansems (2007)
	…made of porcelain	+	n.a.	+	
Core plug	Reusable vs. disposable core plug	n.a.	n.a.	+	Lindahl et al. (2014)
Temporary building	Leasing and modular design enables the reuse of parts of the building vs. being used only once	n.a.	n.a.	+	Smidt Dreijer et al. (2013)
Bedpans	Reusable (or partly reusable) bedpans in different materials, washed in special machine vs. single use	n.a.	n.a.	–	Sørensen and Wenzel (2014)
Incontinence product	Partly reusable incontinence product (reusable pants) vs fully disposable	+	n.a.	+	Willskytt and Tillman (2019)

et al. (1991). An implication is that there are relatively limited RE gains from recycling products where component manufacturing or use phase dominate life cycle impacts instead. Laptops are an example, with energy-demanding component manufacturing, where climate impacts will not be significantly reduced by recycling (André et al., 2019).

For materials and products containing hazardous substances, there is a trade-off, since recycling keeps the hazardous substances in circulation for longer which can lead to their accumulation.

4. Results and discussion

Product characteristics hypothesised to be of relevance for RE were listed in Table 1. Based on the analysis in Section 3, the significance of each characteristic for different measures will here be discussed. Subsequently, some key product characteristics will be identified (see the first row in Fig. 3) and their suitability to different RE measures will be summarised, along with an overview of potential trade-offs.

First, a key distinction is whether a product is *durable* or *consumable*. Much of the discussion on CE concerns durable products and extension of their use, while consumable products, for which use life extension is

Table 10
Studies assessing maintenance, repair and remanufacturing of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
	Maintain				
Window frames	Extended life by improved maintenance, enabled by various material choices (aluminium, wood and PVC)	n.a.	n.a.	+	Carlisle and Friedlander (2016)
Long-haul truck	Functional sales, which enables better maintenance and remanufacturing vs. conventional sales	+	+	+	Chen and Lu (2017)
	Repair				
Washing machine	Extended lifetime by e.g. repairing	+	n.a.	0	Ardente and Mathieux (2014a)
Compressor (in air-condition and refrigerator)	Repaired at site instead of replaced	n.a.	n.a.	+	Biswas et al. (2013)
Vacuum cleaner	Extended lifetime by repairing	+	n.a.	+	Bobba et al. (2016)
Large household appliances, main example: fridges	Increased repair	+	n.a.	n.a.	Domenech and Van Ewijk (2015)
Smartphone	Replacement of components: camera, LCD, batteries, to enable 6 year phone use	+	n.a.	+	Güvendik (2014)
	…plus reuse and refurbishment of replaced components	+	n.a.	+	
Smartphone	Repair of screens, batteries, loudspeakers to enable product use extension	0	n.a.	n.a.	Ljunggren Söderman and André (2019)
Smartphone	Modular vs. conventional design	–	n.a.	–	Proske et al. (2016a)
	…plus replacement and refurbishment of components	–	n.a.	+	
Laptop and mobile phone	Remanufacturing phones and laptops vs. discarding them	n.a.	0	n.a.	Quariguasi-Frota-Neto and Bloemhof (2012)
	Remanufacture				
Compressor for air-conditioning and refrigerator	Remanufactured compressor vs. new compressor	n.a.	n.a.	+	Biswas et al. (2013)
Household appliances	Extended life by remanufacturing of a …dishwasher	n.a.	–	n.a.	Boustani et al. (2010)
	…refrigerator	n.a.	–	n.a.	
	…washing machine	n.a.	–	n.a.	
Large household appliances, main example: fridges	20 % increase in the remanufacturing of large household appliances	+	n.a.	n.a.	Domenech and Van Ewijk (2015)
Photocopier (modular)	Remanufacture of modular photocopier vs. new one	+	+	+	Kerr and Ryan (2001)
Soil compactor	Remanufacture of soil compactor vs. new one	n.a.	n.a.	+	Lindahl et al. (2014)
Alternator	Remanufacture of a lightweight alternator vs. no reman and conventional weight	–	n.a.	–	Schau et al. (2012)
Engine (car)	Extended life by remanufacturing an end-of-life car engine	+	+	+	Smith and Keoleian (2004)
Smartphone	Refurbishment (displacing primary production) vs. new production	n.a.	n.a.	–	Zink and Maker (2014)

Table 11
Studies assessing repurposing of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
Building (commercial)	Selective deconstruction and reuse instead of new construction	n.a.	n.a.	+	Assefa and Ambler (2017)
Smartphone	Repurposing smartphone into parking meter	n.a.	n.a.	+	Zink and Maker (2014)

not relevant, are given less attention. We found it useful to make a further distinction between consumable products used in a dissipative manner (e.g. food and detergents) and disposable products (e.g. packaging). A consumable that is used dissipatively cannot be recycled, but can for example be produced more efficiently and used more effectively. A disposable can in addition be redesigned for multiple use or its material can be recycled.

For *durable* products all the measures aiming for extended use are relevant, in addition to efficiency in production and post-use. Further, aspects pertaining to the use phase are of importance for what RE measures are effective. For active products, use phase efficiency (reduced use of energy or auxiliary material) is important and may even outweigh the benefits of extending the use of the product. For infrequently used products, sharing is a potentially suitable measure, although it does not on its own improve RE for products that tend to be used for their full technical lifetime. Repurposing is suitable for products with remaining functionality at the end of use.

Regarding product complexity and related possibility to disassemble, the collected studies did not allow for systematic testing of their importance. However, *product complexity* is often discussed as a key characteristic for the effectiveness of restorative measures and recycling e.g. in eco-design literature (Ceschin and Gaziulusoy, 2016; Luttropp and Brohammer, 2014; Sundin, 2009) and in Ljunggren Söderman and André (2019). Similarly, the importance of materials of concern could not be tested, although there were examples regarding substitution of scarce metals (Arvidsson et al., 2016; Reuter, 2016).

Among the system level characteristics it is clear that what *phase of the life cycle dominates* resource use and environmental impact is of key importance for what RE measure is effective. This relates to the already discussed active products, for which use phase efficiency is important. For products for which the extraction and production of raw materials dominate, avoiding losses throughout the life cycle becomes important. No correlation between type of industry and the suitability of RE measures could be found in the collected material. Finally, the *pace of development* plays an important role in trade-offs for active products for which use phase efficiency is improved.

In summary, the key product characteristics identified based on the analysis can be found in Fig. 3, which presents and summarises the findings from the analysis. For each key product characteristic it is indicated in colour which RE measure in the typology (from Fig. 2) is suitable to apply in terms of environmental impact and resource use. Additionally, identified potential trade-offs associated with each measure are listed on the right side and described below the figure.

It follows that it is vital to account for product characteristics when implementing RE measures. In contrast, we could not find similar arguments for that prioritised lists of RE measures are suitable for guiding among the many different possible measures. One obvious reason is that not all measures are applicable to all kinds of products. For example, it is not meaningful to consider reuse or remanufacturing of a consumable product such as fuel or food. Another reason is that there exist trade-offs, which need to be assessed on a more detailed level than what e.g. the R-frameworks allow for. Further, RE measures are often interdependent (Blomsma and Brennan, 2017) and several measures often have to be implemented simultaneously, either interacting synergistically or antagonistically (Vezzoli, 2018). The interdependence of measures was also seen in several of the assessment studies reviewed in this paper. One example is the study of reuse of computers which found that a commercial reuse configuration, in addition to granting benefits from extended use, also increases functional recycling since non-reusable computers are effectively collected for appropriate post-use handling (André et al., 2019). More generally, the CE is fundamentally dependent on well-functioning post-use systems. Irrespective of efforts to extend the use of products, post-use handling is required for replaced components and eventually disposed products. Measures for extending the use of products and recycling are thus complementary, why ranking between them is not always meaningful. Yet, in cases where several RE measures can be implemented independently of one another, the R-frameworks might serve as a proxy to prioritise between them. However, the recommendations of an LCA study of four independent RE measures applied in parallel to incontinence products did not conform to what the R-frameworks would recommend (Willskytt and Tillman, 2019), which points to the importance of further clarifying the validity of such frameworks.

We also argue against using type of industry as a basis for decisions on RE measures. Many findings were applicable to several products with characteristics in common, regardless of their industry. Consequently, the suitability of RE measures depend on product characteristics and context rather than type of industry. This supports conclusions by Ghisellini et al. (2018) and Vezzoli (2018), that the outcome of CE solutions depend highly on product system characteristics such as material content, energy efficiency and location.

4.1. Limitations and future research

There are several limitations to our paper leaving room for further research. The study has been concerned with physical measures for RE. In practice, they can be achieved in a number of ways, including new business models and policy interventions. The implications of business models and policies for physical flows of material and energy is a topic for further research. An analysis of post-use measures, purposely

Table 12
Studies assessing recycling the materials of products, describing the difference between RE and reference scenarios and the resulting change in terms of material efficiency (ME), energy efficiency (EE) and environmental performance (EP) (+, − or 0).

Type of product	Change compared to reference scenario	ME	EE	EP	Reference
LCD screen	Manual instead of mechanical disassembly for recycling	n.a.	n.a.	+	Ardente and Mathieux (2014b)
Smartphone	Dismantling and selective smelting instead of smelting of entire phone	+	n.a.	n.a.	Ballester et al. (2017)
	Shredding, physical pre-processing and metallurgy instead of smelting of entire phone	+	n.a.	n.a.	
Paper	Recycling of paper instead of landfilling	n.a.	+	+	Counsell and Allwood (2007)
11 electronic products	Active fasteners used to ease disassembly for recycling	n.a.	n.a.	+	Peeters et al. (2017)
Desktop and laptop computers	Recycling instead of landfill	+	n.a.	n.a.	Van Eygen et al. (2016)

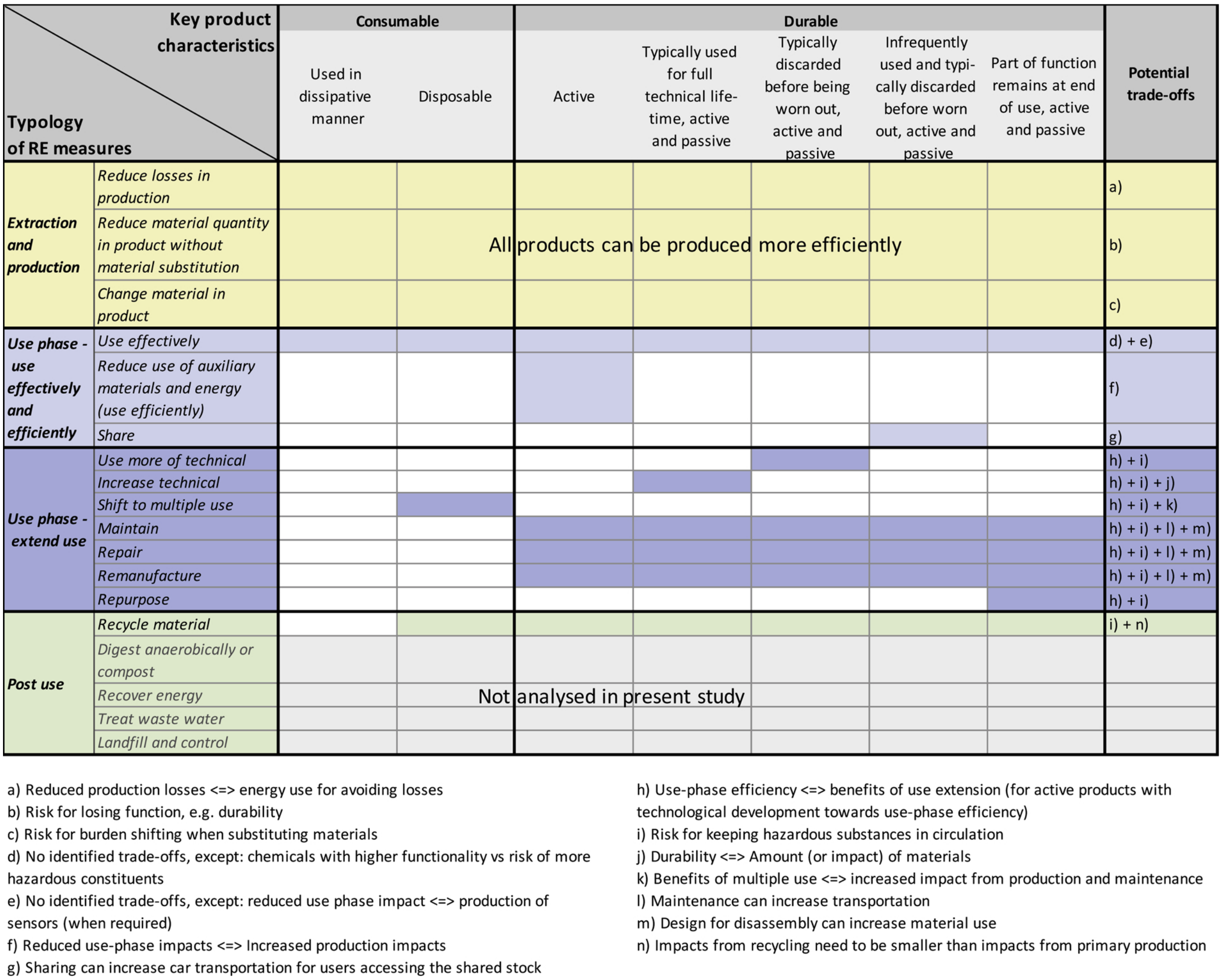

Fig. 3. The product characteristics for which each measure in the typology is suitable (coloured tiles in the centre of the figure), as well as potential associated trade-offs (indexed alphabetically to the right).

excluded in this research, would be relevant. Further, many reviewed studies focus on climate impacts only, with limited assessment of other types of environmental impacts of CE and RE measures. As a consequence, the relevance of *content of concern*, such as hazardous materials and material originating from scarce resources, could not be investigated more than to a limited extent. Moreover, multi-functionality (i.e. a smartphone which is not only a phone but also a radio, camera, music player etc.) can be considered a potential RE measure not included in this study.

As regards the methodology, we note that any quantitative or statistical analysis was forfeited in favour of qualitative synthesis (including a semi-quantitative representation of the results in each assessment study, see Section 2.2.3). A numerical meta-analysis of studies would have required harmonisation of methodological choices such as system boundaries, functional unit etc., which was not possible given the large discrepancy in both object of study, scope and methodology between the studies included in our library.

We identify two main future research needs. Firstly, we recognise that product characteristics are largely a result of design which is an essential precursor to many measures. Hence, there is opportunity to turn recommendations based on product characteristics into design recommendations for RE. Secondly, the fact that many of the reviewed studies are based on desktop assumptions rather than real cases, point to the need for further investigating the importance of real-world complexities and interdependencies.

5. Conclusions

This paper has shown what RE measures are suitable for products with what characteristics (see Fig. 3). Furthermore, the use of a life cycle perspective allowed the identification of potential trade-offs associated with each RE measure. Finally, several key product characteristics of particular importance for the outcome of RE measures were identified. The first is whether products are *consumable*, divided into disposables and products used dissipatively. Second is whether products are *durable*, which can be *active* or *passive* products. Durable products can further be distinguished by whether they are *typically used for their full technical lifetime* or *used infrequently* and *typically discarded before being worn out*. The final key characteristics for durables are the *pace of development* for a product (relevant for durable, active products) and whether *functionality remains after the end of use* of a product. An underlying cause to the importance of several key product characteristics is what life cycle phase *dominates* environmental impact and resource use (e.g. often the use phase for active products). In addition, although our cases did not allow for analysis of its importance, *product complexity* was found from literature to be of key importance. Finally, we argue that product characteristics is a more useful starting point when choosing RE measures than prioritised lists of measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

influence the work reported in this paper.

Acknowledgements

This research was supported by the Mistra REES (Resource-Efficient and Effective Solutions) programme, funded by Mistra (The Swedish Foundation for Strategic Environmental Research) and Chalmers Area of Advance Production. The authors would like to thank the Mistra-REES partners for providing opportunities and support for conducting assessment studies.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104582.

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